ANNUAL PROGRESS REPORT

Case Studies and Diagnostic Models of the Interannual Dynamics of Deforestation in Southeast Asia:
Is the Missing Sink for Carbon in Land Cover Change

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PROGRESS REVIEW

Research Questions Addressed by This Project.

This projects is constructed around two overarching research questions:

1. Are the inter-annual dynamics and rates of deforestation and abandonment to secondary forest significantly different than the decadal mean in Southeast Asia, and can this account for a dampening of the biogenic source of carbon apparent in annual observations of atmospheric carbon dioxide and oxygen?

2. Through the integration of socioeconomic and satellite data and the development of dynamic deforestation models, can we improve our understanding of the dynamics of deforestation in the tropics and the various controls (proximate and distant determinants) on rates of deforestation and regrowth and land use transition sequences?

The project is focused on global change research related to the global carbon cycle, and is thus related to the programmatic objectives of NASA's Mission to Planet Earth, but it concentrates heavily on the specific aspects of land use and cover change rather than biogeochemistry. The results of this work will couple to biogeochemistry and carbon cycle models, but will focus on developing new insights into causes of the fine scale spatial and temporal patterns of cover change. We will use empirical observations from satellites and couple these to integrated models. We propose our research around a framework of Case Studies in intensive study sites and regional analysis for large-scale integration of results.

Research Activities this Year.

Activity 1. Develop Case Studies to determine deforestation dynamics: is secondary growth important and does land use change dynamically on an annual basis; what are the land use transition probabilities?

Activity 2. Determine if the annual rates of deforestation have been significantly different from the decadal mean rate over large areas and the region as whole.

<u>Activity 3</u>. Develop diagnostic models of the deforestation process to better understand and quantify the differential controls on rates of deforestation and abandonment.

RESEARCH RESULTS

Imbalances in the Global Carbon Cycle

Reviews of the global carbon cycle can be found in Houghton and Skole (1990) and Schimel *et al.*. (1995) and we shall cover here only the more salient issues of current uncertainties in the terrestrial carbon cycle. Atmospheric carbon dioxide has increased from 315 ppmv to 356 ppmv in 1992 (Keeling *et al.* 1989, Thoning *et al.* 1994, Keeling and Whorf 1994). With the development of techniques to analyze the concentration of CO_2 in bubbles of air trapped in deep ice cores, it is also possible to estimate the historical atmospheric concentration of CO_2. Since 1750 there has been a steady increase, from 279 ppmv (Neftel *et al.* 1985). Human activities are largely responsible for the observed increases. Fossil fuel burning is currently the most important source of carbon dioxide. Yet evidence from ice cores suggests atmospheric concentrations of CO_2 began to rise prior to 1850, even before significant inputs from fossil fuel combustion. Approximately 30% of the current net flux of carbon dioxide is biogenic and related to anthropogenic land cover changes. Moreover, the long-term historical release of carbon dioxide from human alterations of land cover has been approximately equal to the release from fossil fuel burning (Houghton and Skole 1990).

Net additions to the atmosphere from fossil fuel combustion and biomass oxidation are partly removed by oceanic uptake. However, oceanic uptake from the atmosphere is lower than additions to it, and the atmospheric concentration has risen as a result of this imbalance. Measurements of the atmospheric increase when compared to estimates of the net flux of biogenic carbon, fossil fuel emissions, and ocean uptake cannot be accommodated in a balanced carbon budget. Houghton *et al.* (1983) and Houghton and Skole (1990) have described this situation using a simple equation of the form:

$$\Delta A_t = B + F - O \qquad (1)$$

where ΔA_t is the net increase in the atmospheric carbon at time, *t*, B is the net flux from land clearing and biomass burning, F is the net flux from fossil fuel burning, and O is the net oceanic flux. The units are 10^{15} g C yr^{-1}. When average annual values for individual terms from the period 1980 to 1990 are substituted into the equation (Schimel *et al.* 1995), it is possible to describe the current situation:

$$3.2 \neq 1.7 + 5.5 - 2.0 \qquad (2)$$

There are important uncertainties associated with each of these terms. Nonetheless, the equation is not balanced. Explanations for this imbalance in the budget center on two possibilities. First, the individual terms of the equation may be in error, or improperly modeled -- particularly B and O. The emission from fossil fuels is well known and certain, as are the atmospheric measurements. However, the oceanic and biogenic terms are not. Second, the equation may not be complete, and another term -- the so-called missing sink -- may be important, and hence:

$$3.2 = 1.7 + 5.5 - 2.0 - \beta \quad (3)$$

The recent report of the Intergovernmental Panel on Climate Change (Houghton et $al.$ 1995) suggests several possible mechanisms to explain β, including increased forest C storage due to climate-induced changes in ecosystem metabolism, fertilization by carbon dioxide or nitrogen, or unaccounted land use changes such as forest regrowth. At any rate, the value of this term is rather large (~ 2) and probably cannot be attributed to errors in any one of the other terms alone.

Recent analyses by Tans et $al.$ (1990) and others have suggested a large, unaccounted net sink in undisturbed, predominantly northern, forest ecosystems. The analysis of Tans et $al.$ (1990) utilized a constrained approach, coupling measurements of the north-south gradient of atmospheric [CO_2], measurements of oceanic uptake and $p$$CO_2$, estimates of land surface fluxes from fossil fuels and deforestation, and a general circulation model. The approach provides a geographically-specific assessment of sources and sinks which is highly dependent on the magnitude of the uncertain biogenic tropical source term.

In another constrained analysis, Houghton and Skole (1990) compared a model estimate of the historic net flux of carbon from land cover change with estimates of the total biospheric net flux derived from a deconvolution of ice core data and ocean models (Siegenthaler and Oechgher 1987). This analysis, reproduced in Figure 2, shows general agreement between the estimates prior to about 1930, after which the net flux from land cover change increases while the total biotic flux declines. This suggests either the land use or deconvolution analyses are wrong, or the difference reflects a net sink in undisturbed ecosystems. If a sink in undisturbed ecosystems exists, and is somewhat evenly distributed geographically, the amount per unit area would be too small to measure in the field. Thus, a combination of constrained analyses of this kind and ecosystem models would be required to further elucidate the nature of the sink.

An important consideration in analyses such as Tans et $al.$ (1990) and Houghton and Skole (1990) is knowing the biogenic flux from land cover change, particularly the tropical deforestation component. Improved definition of the imbalance in the global carbon budget will come with better definition of the individual terms of the equation above, with the biogenic term being particularly important. Moreover, the use of constrained analyses, in which additional terms to the equation are inferred as residuals from known terms, will require increased geographical and temporal specificity and confidence in the estimate of biogenic fluxes.

Net Fluxes of Terrestrial Carbon in Asia

Of the combined global net flux of carbon from fossil fuel combustion and land use change in 1990, approximately 30% is from temperate and tropical Asia (Table 1). The global net flux from fossil fuels is ~6.1 x 10^{15} gC yr^{-1} (Marland *et al*. 1994), while the global net flux from land cover conversion is ~1.7 x 10^{15} gC yr^{-1} (Houghton and Hackler 1995). The net flux from fossil fuel combustion in Asia is ~1.5 x 10^{15} gC yr^{-1}, and the net flux from biogenic sources is 0.8 x 10^{15} gC yr^{-1}. The fossil fuel emissions from Asia represent 25% of the global total fossil fuel inputs to the atmosphere, while the biogenic emissions from Asia represent almost half of the global total inputs from land cover change. The contribution of China's fossil fuel emissions is approximately 43% of the regional total fossil fuel emissions, 10% of the regional biogenic flux, and 32% of the combined fossil fuel and biogenic emissions. When we exclude the Pacific Developed countries, which include Japan, Australia, and New Zealand the fossil fuel emissions from Asia are only 18% of the global total fossil fuel inputs of which China's contribution is almost 60%.

Currently this is an important region in terms of its biogenic contribution to the global totals, probably more so than in terms of its contribution from fossil fuels. The Southeast Asia subregion is significant in its contribution of biogenic emissions, contributing almost half of the global total. However, it should be noted that growth rates of fossil fuel emissions since 1970 have been significant in this area of the world, and future emissions of fossil fuel carbon will likely be very high in rapidly developing China and the so-called "Asian Tiger" countries of Southeast Asia. The growth rates in fossil fuel emissions in the last 20 years for China and Southeast Asia have exceed the overall global rate of increase several fold (213% and 240% vs. 49%).

Biogenic Fluxes of Carbon from Land Cover Change in Asian and Other Equitorial Tropical Forests

Human activities have transformed the natural landscape over the past three hundred years in a variety of ways and to varying degrees (Turner *et al*. 1990, Turner and Meyer 1994). Quantitatively, the most important type of change in Asia and elsewhere has been the direct conversion of natural land cover to agriculture (Richards 1984, 1990). Large areas of Asia and other parts of the world are undergoing extensive land transformation as a result of population growth and economic development. Such changes in land cover influence the net exchange of carbon between the land and atmosphere (Detwiler and Hall 1988, Houghton *et al*. 1987, Houghton *et al*. 1985, Houghton *et al*. 1983, Moore *et al*. 1981, Bolin 1983).

Although large releases of carbon are historically attributed to land cover conversion in the temperate zone, tropical deforestation appears to be the major biogenic source of carbon today. The long term cumulative release of carbon from land cover change between 1850 and 1990 is ~122 x 10^{15} g C (Schimel et al. 1995, Houghton 1994). The current annual net flux of carbon from land cover conversion in the tropics is between 0.4 and 2.5 x 10^{15} g C yr^{-1} (Houghton *et al*. 1985, Houghton *et al*. 1987). Ten countries comprise two-thirds of the net

release: Brazil, Columbia, Indonesia, Ivory Coast, Laos, Malaysia, Mexico, Peru, Thailand, and Zaire.

The long term historical net flux of carbon due to land conversion has been documented by analyses based on direct estimates of land use data and ecosystem response characteristics (Houghton and Skole 1990). These studies suggest that while some land transformations increase the amount of carbon stored on land, the overall historical trend has been one of increasing forest conversion to agriculture. This has reduced the amount of carbon stored on land and resulted in a net flux of carbon to the atmosphere. However, as we point out below, most of these analyses have focused on the long term, inter-decadal historical trend, rather than fine temporal analysis of particular years.

The amount of carbon held in terrestrial ecosystems is changed as a result of (1) direct human effects of land use, such as deforestation, and (2) indirect human effects on ecosystems, such as increased concentrations of atmospheric CO_2 or climate change, which influence changes in ecosystem metabolism. At the present time, the net flux of carbon between the biota and atmosphere due to land use change (deforestation) can be calculated with more confidence than changes in carbon storage associated with large- scale changes in ecosystem metabolism. This is because of the large difference in biomass between forests and the agricultural systems which replace them, and because deforestation and reforestation can be readily documented and quantified, particularly if remote sensing data are utilized.

The current net flux of carbon between the biota and the atmosphere due to land use change is uncertain. Three factors contribute to the range of uncertainty: (1) rates of deforestation, (2) the fate of deforested land (i.e. the amount of secondary forest regrowth and re-clearing), and (3) the stock of biomass and soil organic matter and their response to disturbance, including anthropogenic reductions of carbon stocks within forests due to thinning or degradation. Models developed with improved geographic and temporal data on deforestation rates, better parameterization of the dynamic nature of deforestation and reforestation, and improved data on above- and below-ground carbon response characteristics are needed.

In this paper we wish to distinguish between changes in carbon storage due to forest *growth* and changes in carbon storage due to forest *regrowth* and secondary succession. The former has been postulated as a component of the so-called missing sink, resulting from changes in ecosystem metabolism in undisturbed forests. The latter is related to land use changes in areas where significant abandonment of agriculture is taking place. One of the central tenants of this paper is that this latter term has been poorly documented, and that in fact this could be a significant factor in the global carbon budget. Moreover, asynchronies in clearings in one place and time with abandonment and regrowth in other places and times could result in dampened net biogenic sources during certain periods of time. Most estimates of land cover changes are *net* changes; there have been few studies which document both deforestation and regrowth simultaneously and virtually no studies document both processes on an annual basis. Should the relative magnitude of these two processes change significantly from one year to the next, there exists a potential for large temporary variations in the magnitude of the

biogenic source term, and possibly a significantly dampened source term, even while long term trends suggest otherwise.

Interannual Variations in Terrestrial Carbon Fluxes.

Tans *et al.* (1990) used a global circulation model to redistribute atmospheric CO_2 based on surface fluxes of CO_2 from fossil fuel consumption, tropical deforestation, and oceanic uptake. Their analysis predicted that the atmospheric $[CO_2]$ should exhibit a strong north-south gradient of 5.7 to 7.3 ppm. This estimate was significantly higher that the observed meridianal gradient of 3ppm based on the NOAA flask measurements (Tans *et al.* 1990). They discussed that the source of this discrepancy could either be their atmospheric transport model or an unaccounted extra-tropical terrestrial sink in the Northern Hemisphere. Analysis of ^{85}Kr and CFC tracer data indicates that inaccuracies in their transport model could account for differences of only 10% and not the two fold differences measured. Therefore, they assumed that the "missing sink" was a terrestrial sink of 2.0 to 3.4 x 10^{15} gC yr^{-1} in the northern hemisphere temperate zone.

Siegenthaler and Sarmiento (1993) updated the Tans *et al.* oceanic uptake estimates by accounting for differences in ocean skin temperature and bulk water temperature, horizontal transport of carbon from the terrestrial biosphere to the ocean via rivers, and the north-south transport of carbon monoxide and its subsequent uptake in the southern oceans. They conclude that there is a terrestrial sink of about 1.8±1.3 10^{15} gC yr^{-1}, or that the tropical source term of 1.6±1.0 x 10^{15} gC yr^{-1} is too high, or a combination of both.

Quay *et al.* (1992) estimated the net flux of CO_2 in the ocean and biosphere using isotopic measurements of $\delta^{13}C$ (essentially the ratio of $^{13}C/^{12}C$) in the atmosphere and dissolved inorganic carbon from ocean surface waters and atmospheric $[CO_2]$. $\delta^{13}C$ varies depending on the source of the carbon and changes depending on the uptake mechanism due to isotopic fractionation, therefore changes in this ratio provide an indication of the uptake mechanisms (Quay *et al.* 1992, Ciais *et al.* 1995a). Because terrestrial photosynthesis discriminates against the heavier isotope (^{13}C), atmospheric uptake can be partitioned between the ocean and the biosphere (Quay *et al.* 1992, Sarmiento 1993, Houghton *et al.* 1995, Ciais *et al.* 1995a). Quay *et al.* (1992) used this technique to estimate that from 1970 to 1990 the average annual oceanic uptake was 2.1 x 10^{15} gC yr^{-1}, while the average annual terrestrial uptake was negligible (0.1 x 10^{15} gC yr^{-1}).

More recently Ciais *et al.* (1995a, 1995b) applied a hybrid approach using a two-dimensional atmospheric transport model (cf. Tans *et al.* 1990) with $[CO_2]$ and $\delta^{13}C$ measurements from NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL) global flask network (cf. Quay *et al.* 1992) to estimate CO_2 partitioning as a function of latitude and time from 1990 to 1993. These results suggest that the northern temperate zone was a large terrestrial sink (3.5 x 10^{15} g C yr^{-1}) in 1992 and 1993, whereas the northern tropics (from equator to 30°N) are a large source (2.0±1.3 x 10^{15} g C yr^{-1}). This estimate for the northern tropics is considerably higher than the estimate of 0.9 x 10^{15} g C yr^{-1} by Houghton et al. (1987). Ciais *et al.* (1995) attributed this difference to either a problem with their model for intra-hemispheric transport

between the tropical and temperate latitudes or that previous deforestation estimates, particularly for tropical regions such as Southeast Asia have been underestimated.

These results also suggest that the southern tropics were a small terrestrial sink in 1992 and 1993. This is surprising because this latitudinal band contains the Brazilian Amazon and Indonesia. Estimates of CO_2 emission from tropical land use rank these two countries as the top two in terms of total emissions due to deforestation (Houghton *et al*. 1987). The weak terrestrial sink in the southern tropical zone suggests that either the forests have a positive net ecosystem production (due to fertilization of undisturbed forest and/or secondary growth formation) or previous estimates of deforestation have been overestimated (Ciais *et al*. 1995a).

In another approach Keeling and Shertz (1992) and Keeling et al. (1996) relied on new methods for measuring atmospheric $[O_2]/[N_2]$. Photosynthesis converts CO_2 and water into organic carbon and molecular oxygen (O_2). Combustion and respiration pathways work in the opposite direction with the oxidation of organic compounds producing CO_2. Thus, atmospheric $[O_2]$ is a function of photosynthesis, respiration and combustion and varies inversely with atmospheric $[CO_2]$. However, changes in atmospheric $[O_2]$ are difficult to measure because these changes are very small compared with the overall atmospheric concentrations. Nonetheless, changes in $[O_2]$ can still be estimated by changes in the ratio of O_2/N_2 because $[N_2]$ is relatively stable. Since O_2 is not chemically active in the ocean due to its low solubility, changes in atmospheric $[O_2]$ can then be related to fluxes of CO_2 from the biosphere. The net terrestrial exchange of CO_2 can be used to constrain the oceanic CO_2 uptake based on atmospheric measures of CO_2.

Keeling and Shertz (1992) used this technique to estimate an annual oceanic uptake of 3.0 ± 2.0 x 10^{15} gC yr^{-1} and a small annual net terrestrial sink between 1989 and 1991. Keeling et al. (1996) used O_2/N_2 data from 1991-1994 to measure hemispheric gradients in CO_2 uptake. They estimated that overall on an annual basis from 1991 to 1994 the terrestrial biosphere was a net sink of 2.0 ± 0.9 x 10^{15} gC yr^{-1}, tropical land biota was not a strong source or sink, and the oceans were a net sink of 1.7 ± 0.9 x 10^{15} g C yr^{-1}. Using longer term trends in O_2/N_2 they estimated that the measured slow down in the rate of increase in atmospheric CO_2 was due to either increase CO_2 uptake in the temperate land biota or the removal of a net tropical source of CO_2 due to a decrease of deforestation rates or increase in the area in forest regrowth.

These analyses suggest that the tropics are neither a strong source nor a strong sink (Keeling *et al.* 1996). Ciais *et al.* (1995) estimate that the northern tropics are a source, but the southern tropics are a small sink. They propose two explanations for the sink-to-neutral magnitude: (i) an increase in tropical Net Ecosystem Production to offset deforestation sources, and (ii) evidence for a combination of reduced rates of deforestation and increased regrowth of previously cleared land "which underscore the uptake of carbon by recovering forests on land abandoned by shifting agriculture and also suggest reduced clearing rates based on satellite analyses".

Interdecadal and Interannual Land Cover Change In Asia.

The current global rate of deforestation is relatively unknown. Problems documenting it center on: (i) the lack of geographically-referenced data at high spatial resolution derived from a single consistent method for the whole of the tropics -- preferably from satellite data, (ii) a paucity of quantitative information on the relative rates of new deforestation and abandonment to regrowth, and (iii) detailed, annual time-series for specific periods of time from which a complete global carbon budget could be compiled in conjunction with annual atmospheric measurements.

The most recent estimates of the annual rate of tropical deforestation over the last decade by the FAO is 15.4×10^6 ha yr^{-1} (FAO 1993). The regional contributions of this global annual rate are 4.1×10^6 ha yr^{-1} for Africa, 3.9×10^6 ha yr^{-1} for Asia, and 7.4×10^6 ha yr^{-1} Latin America & Caribbean. Within the Latin America & Caribbean region FAO estimated that the rate for Tropical South America was 6.2×10^6 ha, with Brazil alone at 3.7×10^6 ha per year.

Satellite remote sensing is the only means for resolving discrepancies or quantifying temporal and spatial variations in deforestation rates. There are no reasons why satellite-based techniques cannot be applied to a large area like the Amazon basin, or a significant portion of the tropical forest belt, to resolve the aforementioned controversies and uncertainty, and thereby provide vastly improved forcing functions for global carbon models.

In the two sections which follow we report new results of analysis of satellite data for Southeast Asia, an important region in the northern tropics, and the Brazilian Amazon, an important region of the southern tropics.

Methods for satellite data analysis. To analyze what is happening in Asia, Landsat MSS and TM data were acquired for the entire Indochina region, including Thailand, Laos, Burma (Myanmar), Vietnam, and Kampuchea. These data were acquired to compile a complete mosaic of satellite data in the mid 1970s, the mid 1980s and the early 1990s in order to compute synoptic average annual deforestation rates over the last 20 years. At selected test sites we compiled multi-year data for analysis of interannual dynamics.

Digital data are selected from the national or foreign archives and from new acquisitions. These data are preprocessed to standard analysis products. This includes conversion to a common format (CCT-P) from other formats (e.g. CCT-X, CCT-A, and others) and the addition of map coordinates. Each scene is registered to a Universal Transverse Mercator (UTM) map projection using satellite navigation data (includes only system corrections), and the digital image imbedded with coordinate information as UTM labeled tic marks. A 1:250,000 scale photographic 3-band color composite print and a 1:1,000,000 color transparency are also produced and distributed.

These pre-processed data are analyzed for deforestation rates. We use a hybrid methodology based on digital data combined with visual interpretation. Landsat scenes are first georeferenced to "north-up" by using the four corner points provided in the data descriptor

record on the data tape as Ground Control Points (GCPs) to define the linear transformation. The rectification is performed using nearest neighbor resampling technique to minimize convolution of the data.

An iterative, self-organizing (ISO), unsupervised clustering technique is applied to the data with a knowledge-based classifier to produce 5 output classes for our analyses in these regions: forest, non-forest, water, cloud, and cloud shadow. For the ISO analysis in Southeast Asia we first create a new band which is the ratio of band 4 (NIR) to band 2 (RED). We run the unsupervised classification using only band 2 (RED) and this new band. We apply the ISO algorithm to assign 45 output clusters. This algorithm is based on initially using the statistics of the raw data to arbitrarily determine the first clusters. The statistical mean spectral values of clusters are shifted to locate the actual spectral statistics for each cluster. This step is repeated until 95% of the pixel are not reassigned to new clusters during the iterations that shift the cluster means. Assignment of individual pixels to a cluster is accomplished using a minimum spectral distance decision rule such that all pixels are assigned to one of the 45 output clusters. These output clusters are then recoded into a new classification containing up to 5 classes. This is done by overlaying the 45 clusters on the original imagery to aggregate the 45 spectral clusters into the final 5 output classes.

This classification product from is plotted at 1:250,000 scale on vellum and then overlaid on a 1:250,000 scale photo product of the Landsat scene. Polygons that are mis-classified are identified and recoded in the digital geographic information system. The classification product is re-plotted and checked for further editing. These editing steps are repeated until the classification is completed.

To produce databases covering the entire region of analysis, individual scenes are edge-matched and merged to form a seamless mosaic. The mosaic represents a complete inventory of the forest area as it existed in 1973, 1985, and 1992 for all of continental Southeast Asia. Average annual rates of deforestation are computed by difference between dates. It is not possible to compile complete regional coverage each year in order to estimate the actual annual deforestation and regrowth dynamics. In this case we establish several test sites in each region. In the test sites we co-register annual or semi-annual Landsat data and compute change detection analysis for deforested areas and areas in regrowth. For this paper we only report on the regional analysis of continental Southeast Asia for two dates, 1973 and 1985, and our multi-date time-series analysis from 1989 to 1994 for the test site in Chiang Mai, Thailand (Figure 3).

Results from Asia. Results for Southeast Asia are shown in Figures 4 and 5 which show the mapped extent of forest areas at two dates: ca. 1973 and 1985. The numerical summary of results are shown in Table 2. This is the first analysis we know of which reports forest areas and rates of forest loss for the entire region using a single consistent method from satellite data which completely cover the region. It is also the first analysis for the entire region of which we are aware which has been compiled and mapped in a digital geographic information system at a spatial resolution less than 100 meters.

The rate of deforestation from the mid 1970s to the mid 1980s was ~1.4 x10^6 ha yr^{-1}, which is a rate close to that reported for the much larger Brazilian Amazon during the same period (Skole and Tucker 1993). The highest rate of deforestation occurs in Thailand at 0.48 x10^6 ha yr^{-1}, representing approximately 35% of the total for the region. It also has the highest percentage loss rate in the region; approximately 26% of the forest area in 1973 has been lost by 1985. Most of the deforestation in Thailand took place in the northern mountainous region around the province of Chiang Mai and in eastern Thailand along the Cambodian border where shifting cultivation, expansion of commercial agriculture and logging are very active. The total area of Northern Thailand is 169,000 km^2 with 84,000 km^2 (or 49% of the total area) in forest in 1985. By 1993 the Royal Forestry Department of Thailand (RFD) reports that the was just over 75,000 km^2 (or 44%) of forest remaining. This loss of forest corresponds to an annual clearing rate of over 0.11 x 10^6 ha yr^{-1}. During this period from 1985 to 1993 all of Thailand had an average annual deforestation rate of just under 0.2 x10^6 ha yr^{-1}, hence almost 60% of the deforestation occurs in an area less than one third the size of the entire country.

These region-wide results are interesting in that they are higher than that reported by the World Resources Institute (~0.95 x10^6 ha yr^{-1}) for the period 1981-1985 (WRI 1992) and FAO (1.3 x10^6 ha yr^{-1}) for a later period, 1981 to 1990 (FAO 1993). This latter comparison implies that the current estimates from FAO, upon which some carbon flux studies have been based (Houghton 1994), are either too low or the rate has dropped since 1985. Our analysis of Thailand is higher than that reported by the World Resources Institute (~0.25 x10^6 ha yr^{-1}) for closed forests for a later period, 1985-1988 and approximately comparable to those reported by FAO for the later period 1981-1990. At this writing we do not have results from satellite analysis for the entire region for the period 1985 - 1993, but this analysis will be forthcoming soon. Nonetheless, the indications from these data for the entire region and Thailand suggest that rates of deforestation peaked in the late 1980s and then have declined since.

Shifting cultivation is a main land use agent of forest loss in this part of Southeast Asia. United Nations' estimates suggest that shifting cultivation supports about 28 million people in insular and continental Southeast Asia. During the early 1980s FAO estimated that shifting cultivation contributed to 49% of all the deforestation in Southeast Asia (Lanly 1983). FAO estimated that 1 x10^6 ha yr^{-1} ha were in shifting cultivation in Thailand alone at this time. Kammerer (1989) estimated that 500,00 members of hill tribes in Northern Thailand were practicing integral shifting cultivation. In the mid-1980s it was estimated that 0.5 x10^6 ha yr^{-1} of land was under some sort of shifting cultivation cycle in Northern Thailand.

The test site in Chiang Mai (Figure 3) is in the center of this heavy deforestation pressure. Our results of multi-temporal analysis of co-registered annual data from 1986 to 1994 reveals that the area in cultivation increased by 38% from 4.5 x 10^3 ha in 1989 to 6.2 x 10^3 ha in 1994 (Figure 6). From 1989 until 1992 the cultivation area increased annually until it reached 7.4 x 10^3 ha in 1992. The next two years saw a drop in the total cultivated area. During the six year period 1.1 x 10^3 ha of land remained under cultivation, hence the percentage of area in permanent cultivation or in long cultivation cycles (greater than 6 years) varied from 14% to 23% of the total area cultivated at any given time. During this time period 66.2 x 10^3 ha of

the over 81 x 10^3 ha of study area was undisturbed, hence 81% of the area was in long fallow, secondary forest or undisturbed primary forest (not likely since many of the hill tribes prefer to clear primary forest over secondary forest since it leads to higher crop yields).

Figure 7 shows the annual extent of new clearings and abandonment areas. Over the time period of observation the area of new clearings in any given year varied from 2.3 x 10^3 ha in 1990 to a peak of 3.7 x 10^3 ha in 1992 with a decline to 2.4 x 10^3 ha cleared for 1994. In 1990 and 1991 over 50% of the area in cultivation was on areas that had just been cleared. This percentage decreased every year until 1994 when only 39% of the cultivated area was cleared that year. The extent of the abandonment area also fluctuated significantly over this time period. The smallest abandonment occurred from 1990 to 1991 with only 1.8 x 10^3 ha abandoned, while the extent of abandonment almost doubled to 3.5 x 10^3 ha and 3.4 x 10^3 ha in 1993 and 1994, respectively.

These results of the multitemporal analysis suggest that deforestation rates are highly variable from one year to the next and that the process of deforestation involves considerable abandonment to fallow, or secondary forests. The rate of abandonment is also highly variable and sometimes not synchronous with clearing (i.e. one could have years with large amounts of fallow formation and very little new deforestation). Carbon accumulating regrowth is a predominant feature of the Asian landscape. The overall trend in the region appears to be characterized as having rates of deforestation peaking in the late 1980s and the declining somewhat in the 1990s. As this "pulse" of deforestation passes through the system as a general *interdecadal* trend which would suggest increased carbon emissions, the high variation in rates of clearing and abandonment (which are not necessarily occurring simultaneously) could create *interannual* periods in which the annual carbon flux is characteristically different than the *decadal* trend.

More work is underway at this time to test these ideas in other locations throughout the tropics on an interannual basis and to develop region-wide analyses for more recent time periods, such as 1985-1993 and 1993-1996.

Comparison with Results from Other Tropical Regions.

Regional Analysis in the Brazilian Amazon. Analyses of satellite data for the Brazilian Amazon indicate that from 1978 to 1988 the average annual rate of deforestation was between 1.6-2.2 x10^6 ha per year (INPE 1992, Skole and Tucker 1993). Our own work-in-progress for the suggests that the annual rate of deforestation in the Brazilian Amazon peaked during the period 1978-1986 at around 1.8 x 10^6 ha yr^{-1} and then declined to ~1.4 x 10^6 ha yr^{-1} from 1986 to 1993.

The Brazilian Space Agency, INPE, reports annual deforestation rates from 1988-1991 for the Legal Amazon of ~1.9, 1.4, and 1.1 x10^6 ha yr^{-1}, respectively, for this three year time period (Alves, pers. comm.). The 1990-1991 rate was 67% less than the average rate for this

three year census. Apparently, the deforestation rate from 1990-1991 was half of the average annual rate from 1978 to 1986.

Other data from the Brazilian Amazon suggest large differences in deforestation rates and the existence of large areas of abandonment each year (Alves and Skole 1996, Skole *et al.* 1994). Approximately 30% of the deforested areas in the Amazon are in secondary growth. From a few site studies in which interannual time series data have been acquired, it has been shown that the abandonment rate can be as high as 82% of the deforestation rate (1991-1992 in Alves and Skole 1996). At the same time, the deforestation rate varied annually by as much as 100% with an average over 6 years of 50%.

These results bolster those reported here from Southeast Asia and give strong indications that there are indeed significant influences of interannual changes in the deforestation rate on net fluxes of carbon, but without further analyses in more sites it is not possible to draw final conclusions.

The Significance of Secondary Growth.

Results reported here for Southeast Asia indicate extensive areas of forest fallow and secondary growth in Continental Southeast Asia exist. Similar results exist for the Legal Amazon. For example, 30% of the deforested area in the Legal Amazon is in some form of secondary growth in 1986 and 1992. This percentage represent areas over 77,000 km^2 and 98,000 km^2 in secondary growth in 1986 and 1992, respectively.

Satellite analysis by Alves and Skole (1996) indicate that for a site in Rondonia, Brazil, secondary growth is a large (over 40% of the deforested areas) and a rapidly changing pool. Almost 60% of the areas in secondary growth in 1986 were re-cleared at least once by 1992, and over 55% of the deforested areas in 1986 were abandoned into secondary growth for some period of time by 1992 (Alves and Skole 1996). This analysis and other similar satellite based analyses (Steininger 1996, Foody *et al.* 1996, Brondizio *et al.* 1994, Moran *et al* 1994, Lucas *et al.* 1993, Mausel *et al.* 1993) are useful for characterizing the dynamics of the secondary growth resulting from tropical land use and support similar evidence reported here for Southeast Asia.

These studies of deforestation from satellite data show it is a highly dynamic process of clearing, abandonment and re-clearing, and the rates at which land is cleared or abandoned are related to the land use and management system the forest farmers employ. In some cases, deforestation and secondary succession exist in tandem as a tightly coupled system in which secondary growth is continually recycled back into farmland. In other cases active land management maintains the land in agriculture, or the lack of active land management or population displacement results in long-term succession.

Thus land *use* change influences land *cover* change and is integrated with dynamics of ecosystem structure, function, and response. Within a focused research program, it will be

important to frame such questions as: what human land-use and land management strategies are employed in different situations and how do they control , or interact with, the dynamics of ecosystem response to disturbance? Because deforestation and abandonment have opposite effects on atmospheric carbon dioxide (c.f. uptake vs. release), we can re-state the aforementioned general question in terms specific to the carbon cycle: over time what land use strategies determine the abundance and spatial distribution of secondary growth, how do they determine the balance between clearing and regrowth rates, and how are these land use strategies in turn influenced by ecological conditions?

Implications of Recent Carbon Cycle Analyses for Tropical Deforestation Rates.

Analysis for specific recent years (cf. 1992-1994) reported by Keeling *et al*. (1996) and Ciais *et al*. (1995) which suggest that the tropics as a whole, and the southern tropics in particular, are not large sources of biogenic carbon are somewhat inconsistent with interdecadal results from previous terrestrial carbon models based on land use change by Houghton and Skole (1990), Houghton (1994) and others, and recent observations from satellite analyses of deforestation rates for Southeast Asia (see below) and the Amazon (Skole and Tucker 1993) which suggest that tropical deforestation has contributed to a significant net source of carbon.

Based on results presented above, an explanation worth exploring further is that pervious estimates of the tropical source term were based on decadal mean values, rather than explicitly on any specific year or set of years when atmospheric measurements are made (cf. 1992-1994). This would be especially relevant if tropical land use change is characterized by large areas and rates of abandonment with significant inter-annual variation as appears to be the case in both Southeast Asia and the Amazon. Significant interannual differences in the long term trend in deforestation rates and the relative rates of deforestation and abandonment could result in periods of asynchrony where clearing rates, which relate to carbon emissions, and abandonment rates, which relate to carbon uptake are very different. Such dynamics would result in wide interannual variations in the relative contribution to the net flux from clearing vs. regrowth, and, potentially, a dampening in the decadal mean values for particular years.

In this scenario two important conditions must be met: (1) large *interannual* departures in rates of deforestation from the *decadal mean* values reported by previous analyses, and (2) large areas of forest regrowth as a result of land abandonment. In years in which deforestation rates are greatly less than the decadal mean, and with the large abundance of areas of secondary succession and forest regrowth due to high rates of abandonment in previous years we would expect to see a significant dampening of the carbon source computed from the decadal mean data alone.

These issues then beg a very interesting suite of questions concerning the factors which *cause* deforestation rates to vary from year to year, and what factors determine or control the balance between clearing and abandonment. The resolution of such questions depends completely on: (1) making fine temporal resolution measurements (annually) of deforestation rates over large areas using satellite remote sensing, (2) making fine spatial and temporal

scale analyses of the dynamics of land use and cover change in order to document if regrowth is a significant factor, and (3) developing an improved quantitative and diagnostic capability to determine the factors (i.e. the so-called Human Dimensions) which control relative rates of clearing and regrowth from one year to the next.

An Approach to IGBP and IHDP Research in Tropical Asia.

To better quantify and understand the significance of interannual changes in the rate of deforestation and abandonment, the IGBP could undertake a research effort in Southeast Asia which is described below. It would be comprised of four central activities, which could be carried out through collaboration of several Program Elements of the IGBP and IHDP, particularly LUCC, GCTE, IGAC and GAIM. Additional participation of DIS and START would be essential framework elements.

Activity 1. Determine the decadal mean rate of forest loss for the region from 1986 to 1996 using a two-date complete inventory of satellite data.

This work would be similar to that described in this paper but updated to include the addition of one more date circa 1996. This could readily be achieved through collaboration with satellite observation programs already in place such as the NASA Landsat Pathfinder project whose results are reported in this paper, Japanese efforts now underway, and several European Union projects such as the TREES project. This effort provide an additional inventory year in 1996 to determine the average rate of change from 1986 to 1996.

Activity 2. Determine if *annual* rates of deforestation have been significantly different from the decadal mean rate over large areas and the region as whole.

This activity would be developed to define the interannual rate of deforestation for the region as a whole using stratified sampling based on the decadal complete inventories using the results described above as a starting point. A stratified sampling scheme in Southeast Asia could be easily developed and then implemented to estimate the annual change in forest area from 1986 to 1994, the time-frame relevant to atmospheric CO_2 and O_2 measurements. This analysis would focus only on forest to non-forest, and provide a single region-wide estimate which can be used to interpolate annually between the average rates of forest loss estimated by Activity 1.

Activity 3. Develop Case Studies aimed at the following question: is secondary growth important and does land cover change dynamically on an annual basis; what are the land use transition probabilities?

In 5-8 selected case study sites the inter-program-element project would analyze annual time series of satellite data from 1986 to the present to calculate transition sequences and their associated probabilities for deforestation and secondary growth. Each case study would be an area as large as a single Landsat scene and could be located in the following countries of the

region: Thailand, Laos, Vietnam, Indonesia, Malaysia, and the Philippines since there exists already an ongoing precursor project being developed under START and LUCC. It would be desirable to evaluate the addition of two other sites in Myanmar and Kampuchea. Each case study would focus on estimating the transition matrix for the following classes: Forest, secondary growth, paddy, upland crops, tree crops, and urban/developed.

To carry out the Case Studies it will be necessary to solicit the collaboration of a well-established team of regional scientists through the START programs and in collaboration with established groups which have been working since 1993 as part of an IGBP/IHDP Land Use and Cover Change (LUCC) project in Southeast Asia.

Activity 4. Develop diagnostic models of the deforestation process to better understand and quantify the differential controls on rates of deforestation and abandonment.

The causes of deforestation have often been attributed to such things as population growth, road building, and a host of other similar monotonically varying variables (Panayotou 1991). Although population and infrastructure are important long term determinants of general trends over decades, interannual variability is not tightly linked to such parameters. Econometric variables such as variations in price structures and local market demands are likely to be better predictors of deforestation and abandonment rates over short time cycles. This activity would couple the satellite-based deforestation dataset derived from the aforementioned activities to socio-economic data to build diagnostic models of the deforestation process.

Such models can provide: (a) an improved understanding of the factors which control variations in deforestation rates annually, (b) an improved understanding of the factors which determine the balance between creation of new farmland through deforestation and the creation of new farmland by clearing secondary fallow forests, (c) an improved understanding of the factors which control the balance between deforestation (the bringing of land into production) and abandonment (the taking of land out of production), and (d) a method for spatial and temporal extrapolation of the results from the Activities described above.

These models should be developed at two levels. The first would be focused on each of the Case Study sites with an emphasis on establishing the critical village-level variables, dynamics and proximate determinants. The second level of model analysis would be at the scale of countries or the region. The Case Studies will be used to calibrate the regional model and provide a basis and location for validation of regional results.

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Table 1: Terrestrial Carbon Emissions from Fossil Fuel Consumption and Land Cover Conversion in Asia, 1990 (units are 10^{15} g C yr^{-1})
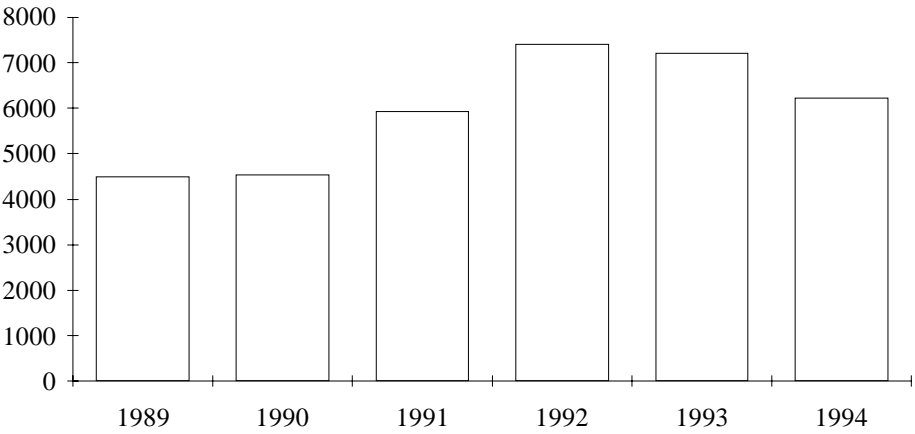
Region or Country	Fossil fuel flux	% of global fossil fuel (combined)	% increase since 1970	Biotic flux	% of global biotic (combined)	% increase since 1970
Global	6.10	NA	49	1.70	NA	28
Asia	1.53	25 (20)	156	0.80	47 (10)	52
China	0.66	11 (9)	213	0.08	5 (1)	-42
South and SE Asia	0.50	8 (7)	240	0.70	41 (9)	139
Pacific Developed	0.38	6 (5)	52	0.01	1 (<1)	-88

Table 2. Summary of results from satellite data analysis of forest areas and their rate of change in continental Southeast Asia. (units are 10^6 ha. or 10^6 per year)

Country	Forest Area in 1973	Forest Area in 1985	Forest Area Change	% Change	Deforestation Rate per year
Cambodia	5.25	3.98	1.27	24	0.11
Laos	18.28	16.52	1.76	10	0.15
Thailand	22.56	16.74	5.81	26	0.49
Vietnam	19.92	16.15	3.77	19	0.31
Myanmar	48.71	44.82	3.88	8	0.32

Total	114.70	98.21	16.49	14	1.37

Area in Cultivation

Annual Transitions